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Discovery of counter-rotating gas in the galaxies NGC 1596 and NGC 3203 and the incidence of gas counter-rotation in S0 galaxies

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ABSTRACT

We have identified two new galaxies with gas counter-rotation (NGC 1596 and NGC 3203) and have confirmed similar behaviour in another one (NGC 128), this using results from separate studies of the ionized-gas and stellar kinematics of a well-defined sample of 30 edge-on disc galaxies. Gas counter-rotators thus represent $10\pm5\%$ of our sample, but the fraction climbs to $21 \pm 11\%$ when only lenticular (S0) galaxies are considered and to $27 \pm 13\%$ for S0s with detected ionized-gas only. Those fractions are consistent with but slightly higher than previous studies. A compilation from well-defined studies of S0s in the literature yield fractions of $15 \pm 4\%$ and $23\pm5\%$, respectively. Although mainly based on circumstantial evidence, we argue that the counter-rotating gas originates primarily from minor mergers and tidally-induced transfer of material from nearby objects. Assuming isotropic accretion, twice those fractions of objects must have undergone similar processes, underlining the importance of (minor) accretion for galaxy evolution. Applications of gas counter-rotators to barred galaxy dynamics are also discussed.

Key words: galaxies: individual: NGC 128, NGC 1596, NGC 3203 – galaxies: kinematics and dynamics – galaxies: nuclei – galaxies: evolution – galaxies: ISM – galaxies: interactions.

1 INTRODUCTION

It has been already almost 20 years since the phenomenon of counter-rotation in disc galaxies was discovered (Galletta 1987), but both the exact incidence and the origin of counter-rotating gas and stars remain to be clarified. Most statistical studies indicate that roughly 20–25% of all lenticular (S0) galaxies with detected ionized-gas (usually observed through optical emission lines) contain a non-negligible fraction of gas-stars counter-rotation (e.g. Bertola, Buson & Zeilinger 1992; Kuijken, Fisher & Merrifield 1996; Kannappan & Fabricant 2001; Pizzella et al. 2004), typically in the central regions. The fraction is much lower in later type systems (e.g. Kannappan & Fabricant 2001; Pizzella et al. 2004), presumably because co-rotating and counter-rotating gas can not coexist at a given radius. Galaxies with counter-rotating H I or CO gas are also known (e.g. NGC 4826, Braun, Walterbos & Kennicutt 1992; NGC 3626, Garcia-Burillo, Sempere & Bettoni 1998), but to our knowledge no sound statistics exists. The fraction of S0s with stars-stars counter-rotation is also much lower (at most 10% but perhaps lower; Kuijken et al. 1996; Pizzella et al. 2004), perhaps due to the increased difficulty of detecting small numbers of counter-rotating stars. Generally, however, the number of objects on which well-defined studies are based is still rather small, and it is still the case that most known counter-rotators were discovered fortuitously in targeted studies (e.g. NGC 4546, Galletta 1987; NGC 4138, Jore, Broeils & Haynes 1996).

Our goal in this paper is thus to improve the (ionized-gas) counter-rotation statistics in S0 galaxies and summarize the current situation. Since counter-rotating material is a strong argument in favour of hierarchical galaxy formation scenarios, this is an important goal. In the interest of conciseness, we do not discuss here the issue of counter-rotation in elliptical galaxies, although it is probably related (see Rubin 1994 and Schweizer 1998 for general reviews of galaxies with misaligned angular momenta).

In Section 2, we describe gas and stellar kinematics observations of a large sample of edge-on disc galaxies. The

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structure, kinematics, and environment of 2 newly discovered ionized-gas counter-rotators and 1 known object are discussed in detail in Section 3. In Section 4, we quantify the incidence of counter-rotators using all available observations and discuss their possible origin through continuous gas infall and/or discrete gas and satellites accretion. Applications of gas counter-rotators to barred galaxy dynamics are also discussed. We conclude briefly in Section 5.

2 OBSERVATIONS

2.1 Sample and data reduction

Our sample consists of 30 edge-on disc galaxies from the catalogs of galaxies with a boxy or peanut-shaped (B/PS) bulge of Jarvis (1986), Shaw (1987) and de Souza & dos Anjos (1987), and from the catalog of galaxies with an extreme axial ratio of Karachentsev, Karachentseva & Parnovsky (1993). 80% have a B/PS bulge and roughly three-quarters either have probable companions or are part of a group or cluster, although some are probably chance alignments so the sample is not biased either against or for galaxies in a dense environment. We warn that the usual morphological classification into Hubble type (e.g. Sandage 1961) is uncertain for edge-on galaxies, since the bulge-to-disc ratio is effectively the only usable criterion.

The observations from the Double Beam Spectrograph on the 2.3-m telescope at Siding Spring Observatory were already discussed elsewhere. The red arm of the spectrograph, used to study the ionized-gas kinematics of the sample galaxies (Bureau & Freeman 1999), was centred on the Hα λ6563 emission line, covering roughly 950 Å with a spectral resolution of 1.1 Å (50 km s^{-1}). The blue arm, used for the stellar kinematics (Chung & Bureau 2004), was centred on the Mg*b* λ5170 absorption triplet, covering again roughly 950 Å with a 1.1 Å (50 km s^{-1}) spectral resolution. The seeing was typically 1.0–1.5 arcsec. All data were reduced and analysed using standard software and methods and we refer to Bureau & Freeman (1999) and Chung & Bureau (2004) for further details. We note that we have not extracted ionized-gas rotation curves from our data, the entire two-dimensional spectra or position-velocity diagrams (PVDs) constituting our final products.

2.2 Results

By comparing the ionized-gas and stellar kinematics, 3 galaxies out of the sample of 30 show clear ionized-gas counter-rotation. That is, the ionized-gas is rotating in the opposite direction to the bulk of the stars. Those galaxies, along with their ionized-gas and stellar kinematics, are shown in Figure 1. We note that the orientation of the slit was inverted for NGC 128 and NGC 1596 in Chung & Bureau (2004), and it has been corrected here. This has however no bearing on the detection of counter-rotation. Basic properties of the galaxies are listed in Table 1. NGC 128 is a well-studied case (e.g. Emsellem & Arsenault 1997; D'Onofrio et al. 1999), but counter-rotation in NGC 1596 and NGC 3203 is reported here for the first time.

As in many previous cases (e.g. Bertola et al. 1992), the

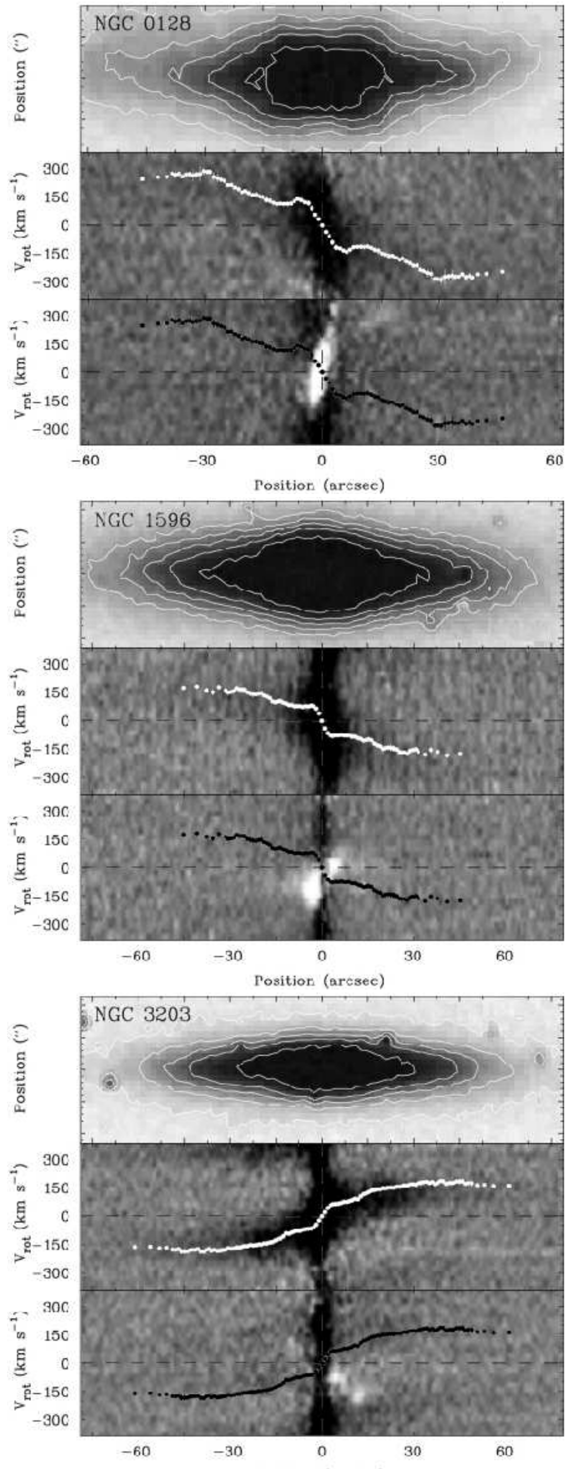

Figure 1. Stellar and ionized-gas kinematics of NGC 128 (top), NGC 1596 (middle) and NGC 3203 (bottom). Each panel shows, from top to bottom and spatially registered, a grayscale image of the galaxy (with contours) from the Digitized Sky Survey (DSS), the stellar rotation curve (white dots) overplotted on a stellar absorption line, and the stellar rotation curve (black dots) overplotted on an emission line position-velocity diagram (here [OIII] λ5007). For all three galaxies, the ionized-gas is clearly limited to the central regions and counter-rotating with respect to the stars.

Table 1. Basic properties of the galaxies with gas counter-rotation

Quantity	NGC 128	NGC 1596	NGC 3203	Source
Right ascension (J2000)	$00^{\rm h}29^{\rm m}15\overset{\rm s}{.}0$	$04^{\rm h}27^{\rm m}38\overset{\rm s}{.}1$	$10^{\rm h}19^{\rm m}33\overset{\rm s}{.}8$	NED
Declination (J2000)	$+02°51'51''$	$-55°01'40''$	$-26°41'56''$	NED
Heliocentric velocity (km s^{-1})	4241	1510	2424	NED
Distance (Mpc)	60.3	17.5	32.4	HyperLeda
Morphological type	S0 pec	SA0:	SA(r)0$^+$?	NED
Apparent diameter (arcmin; $\mu_B = 25$ mag arcsec^{-2})	3.0×0.9	3.7×1.0	2.9×0.6	NED
Total apparent B magnitude	12.7	12.0	13.0	HyperLeda
Total absolute corrected B magnitude	−21.4	−19.3	−19.9	HyperLeda

NED: NASA/IPAC Extragalactic Database: http://nedwww.ipac.caltech.edu/index.html
HyperLeda: http://www-obs.univ-lyon1.fr/hypercat/

counter-rotating gas is limited to the inner bulge-dominated region of the galaxies, with radial extent of order 1 kpc. However, since the ionized-gas is clearly asymmetric, since its extent clearly depends on the depth of our spectra and on our ability to recover emission lines, and since our spectra are not flux calibrated, we refrain from discussing the exact sizes and masses of the counter-rotating discs.

Suffice it to say that while the ionized-gas appears fairly regular in NGC 128 and NGC 1596, it is rather unsettled in NGC 3203. Except for a hint of ionized-gas at large positive velocities in NGC 128, the ionized-gas detected always appears confined to a region with rising, approximately solid-body rotation. We refrain from plotting velocity dispersion measurements, as the emission lines are generally unresolved spectrally. We also note that our long-slit observations can not constrain the exact alignment of the ionized-gas. The observed counter-rotation only implies a kinematic (and angular momentum) misalignment between the stars and ionized-gas between 90 and 270°.

While the ionized-gas in NGC 128 is consistent with being in a ring (which, if circular, yields a straight line in a PVD), that in NGC 1596 clearly is not, or at least the ring must have a significant width. A ring of ionized-gas in NGC 3203 could only explain the observations if very patchy; it is more likely that the gas is substantially disturbed.

To gauge the immediate environment of the galaxies, 15 arcmin × 15 arcmin DSS images of NGC 128, NGC 1596 and NGC 3203 are shown in Figure 2.

3 THE GALAXIES

3.1 NGC 128

NGC 128 (S0 pec) is the prototype of galaxies with a B/PS bulge, being recognized as such already in Burbidge & Burbidge (1959), Sandage (1961), and Hodge & Merchant (1966). Good quality optical and near-infrared (NIR) surface photometry is available in de Carvalho et al. (1991) and Terndrup et al. (1994), respectively, as well as later publications (e.g. Emsellem & Arsenault 1997; D'Onofrio et al. 1999). Shaw, Dettmar & Barteldrees (1990) attempted to quantify the main global parameters describing the peanut shape of the bulge (but see also Schwarzkopf & Dettmar 2000a,b, 2001; de Souza et al. 2004).

Bertola & Capaccioli (1977) first discussed the stellar rotation curve of NGC 128 and detected its "double-hump" structure, nicely confirmed by D'Onofrio et al. (1999). Although ionized-gas emission had already been detected, Kuijken et al. (1996) first pointed out that it is counter-rotating. Emsellem & Arsenault (1997) and D'Onofrio et al. (1999) published comprehensive studies of the structure and stellar/ionized-gas kinematics of NGC 128, confirming the counter-rotation of the ionized gas and showing that it is tilted by ≈ 25–40 deg with respect to the main (equatorial) plane of the galaxy (see also Monnet et al. 1995; D'Onofrio et al. 1997). The main disc and B/PS structure have largely identical and uniform colours (see also Terndrup et al. 1994), but the counter-rotating disc is visible as a slight reddening in the central regions and is thus probably dusty. Relying on N-body simulations (e.g. Combes & Sanders 1981; Combes et al. 1990), the peanutness of the isophotes, the counter-rotating but tilted ionized-gas disc (see Section 4.3) and the gaseous cylindrical rotation, Emsellem & Arsenault (1997) argued that the peculiar shape of NGC 128 is due to an edge-on bar viewed nearly side-on. D'Onofrio et al. (1999) also convincingly showed cylindrical rotation in the stars, as expected for barred galaxies viewed edge-on (e.g. Combes et al. 1990), and a plateau in the major-axis light profile, traditionally associated with edge-on bars (see, e.g., Bureau & Athanassoula 2005 and references therein). Chung & Bureau (2004) later used the characteristic shape of the stellar kinematic profiles (V, σ, h_3 and h_4) to argue along similar lines.

NGC 128 is in a compact group and is clearly interacting with its neighbors NGC 127 (SA0^0; $\Delta V \approx 190$ km s^{-1}) and NGC 130 (SA0$^-$; $\Delta V \approx 190$ km s^{-1}). Beckman et al. (1990) briefly explored the dynamics of the triplet. The galaxies NGC 125 ((R)SA0+ pec; $\Delta V \approx 1065$ km s^{-1}) and NGC 126 (SB0^0; $\Delta V \approx 10$ km s^{-1}), slightly farther away but also visible in Figure 2, are also part of the same group (although NGC 125's redshift is rather high). To our knowledge, no gas is detected within the central parts of the group except for NGC 128's counter-rotating disc. Dust is however present and peaks where NGC 128 interacts with NGC 127 ($\gtrsim 6 \times 10^6$ M$_\odot$ of dust; D'Onofrio et al. 1999) and NGC 125 has an H I detection (Chamaraux et a. 1987). New improved H I observations will also be presented in a future publication (in preparation).

A search within a projected radius $R = 0.5$ Mpc from NGC 128 using NED reveals many other possible companions, most with unknown redshifts but a number with similar

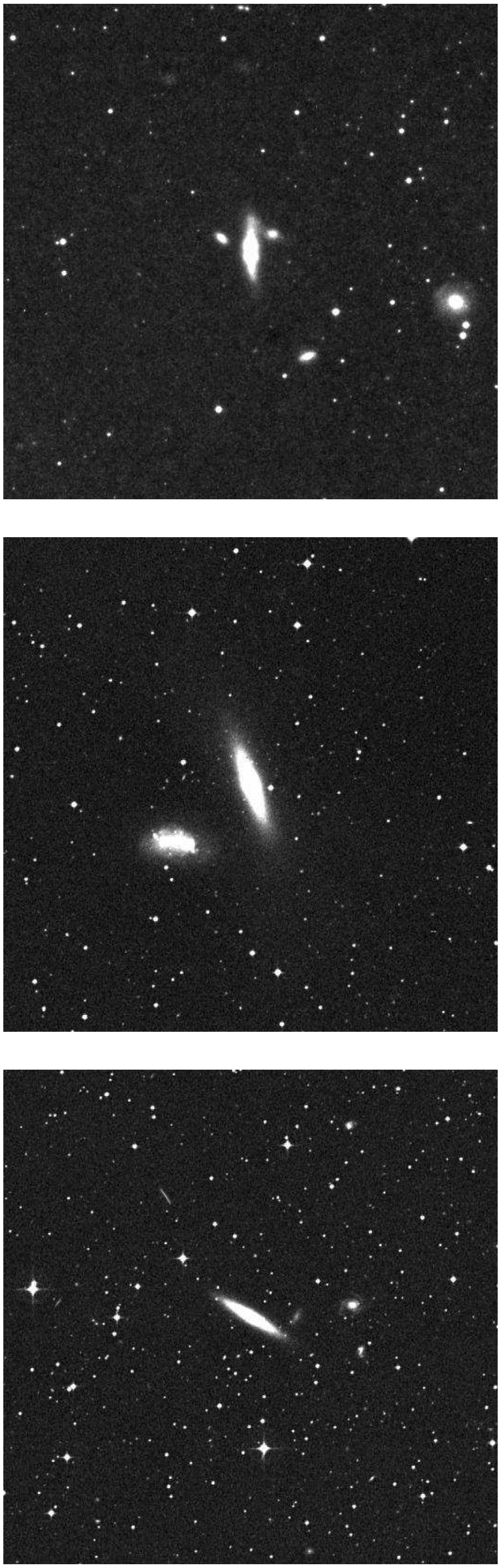

Figure 2. Immediate environment of NGC 128 (top), NGC 1596 (middle) and NGC 3203 (bottom). Each panel shows a 15 arcmin $\times$ 15 arcmin DSS image centred on the galaxy, with the usual orientation of North up and East to the left.

ones: UGC 286 (Sbc; $\Delta V \approx 230$ km s^{-1}; $R = 0.19$ Mpc), IC 17 (S; $\Delta V \approx 75$ km s^{-1}; $R = 0.30$ Mpc), UGC 281 (Scd; $\Delta V \approx 55$ km s^{-1}; $R = 0.42$ Mpc), LSBC F824-10 (dI; $\Delta V \approx 175$ km s^{-1}; $R = 0.45$ Mpc), UGC 277 (Scd; $\Delta V \approx 120$ km s^{-1}; $R = 0.47$ Mpc) and UGC 275 (SAB(rs)b pec; $\Delta V \approx 145$ km s^{-1}; $R = 0.50$ Mpc). Many are H I-rich. See also Garcia (1993), Giuricin et al. (2000), Focardi & Kelm (2002) and Ramella et al. (2002) for studies of group membership.

3.2 NGC 1596

Little detailed information on NGC 1596 is available in the literature. As for NGC 128, Shaw et al. (1990) quantify the global parameters describing the boxy shape of the bulge, while Jorgensen, Franx & Kjaergaard (1995) present more general global results, also from optical surface photometry. A more detailed analysis by Pohlen et al. (2004), who attempted but failed to fit a thin plus thick disc model, reveals an extended, roughly speroidal but somewhat distorted outer envelope, which they suggest might be related to an interaction with NGC 1602 (see below). Bothun & Greg (1990) obtained both optical and NIR photometry and showed that, like most of their S0 sample, the NIR-NIR colors of the bulge and disc of NGC 1596 are similar, indicating a similar metalicity, while the optical-NIR colors are significantly different, suggesting a younger disc (in the mean).

The only spatially resolved kinematic observations available for NGC 1596 are the current ionized-gas kinematics and the stellar kinematics of Chung & Bureau (2004), who argued that the B/PS bulge of NGC 1596 is due to an edge-on bar viewed nearly end-on.

NGC 1596 forms a pair and is most likely interacting with the H I-rich galaxy NGC 1602 (IB(s)m pec; $\Delta V \approx 60$ km s^{-1}) only 3.0 arcmin away and easily visible in Figure 2. There are again many other possible companions within a 0.5 Mpc projected radius, but only three galaxies have a similar known redshift: NGC 1581 (S0^{-}; $\Delta V \approx 90$ km s^{-1}; $R = 0.13$ Mpc), ESO 157-G 030 (E4; $\Delta V \approx 40$ km s^{-1}; $R = 0.25$ Mpc), and NGC 1566 (R$'$SAB(rs)bc; $\Delta V \approx 5$ km s^{-1}; $R = 0.34$ Mpc). See also Maia et al. (1989), Giuricin et al. (2000) and Kilborn et al. (2005) for studies of group membership. NGC 1596 was not detected by *IRAS* but is apparently H I-rich (e.g. Reif et al. 1982; Kilborn et al. 2005), although it is unlikely that a single-dish telescope could disentangle its flux from that of NGC 1602. Recently acquired H I synthesis observations will clarify the issue (Chung et al. 2006).

3.3 NGC 3203

No in-depth study of NGC 3203 exists in the literature, although de Grijs & Peletier (1997) present broadband optical imaging and argue for an increasing disc scaleheight with (projected) radius, which they attribute to the gradual dominance of a thick disc over the thin disc. de Grijs & Peletier (2000) however show that NGC 3203 has no discernable vertical colour gradient. de Grijs, Peletier & van der Kruit's (1997) K'-band data also suggest a change in the steepness of the vertical light distribution near the centre, contrary

to most galaxies in their sample. Because of the particular shape of the K' light profiles along cuts parallel to but offset from the major-axis, which display a characteristic plateau and secondary maxima, Lütticke et al. (2000) argue that NGC 3203 is barred.

While little is known about the dynamics of NGC 3203, except for the ionized-gas kinematics presented here and the stellar kinematics of Chung & Bureau (2004), the latter also argue that the B/PS bulge of NGC 3203 is due to an edge-on bar viewed nearly end-on.

NGC 3203 has many possible companions within $R = 0.5$ Mpc, but none with a known similar redshift: NGC 3208 (SAB(rs)bc; $\Delta V \approx 470$ km s^{-1}; $R = 0.5$ Mpc) has a rather high systemic velocity. NGC 3203 was not detected by *IRAS* or in H I, but new improved H I observations will appear in a future publication (in preparation).

4 DISCUSSION

4.1 Incidence of gas counter-rotation

Bertola et al. (1992) presented the first rigorous statistical study of counter-rotating or strongly kinematically decoupled ionized gas in disc galaxies (see also Bertola et al. 1995). They identified 3 gas counter-rotators in a sample of 15 bright and nearby S0s with extended ionized-gas ($20 \pm 10\%$ for 1 standard deviation assuming a binomial distribution), suggesting that at least 40% of such objects may have acquired their gas externally (assuming randomly oriented infall). Given that pre-existing co-rotating gas (e.g. due to stellar mass loss) will tend to decrease the fraction of observed counter-rotating systems (due to shocks and the associated loss of angular momentum), the true fraction of objects with significant external gas accretion is probably even higher. Although it does not change their conclusions, it is worth noting that Bertola et al. (1992) missed the gas counter-rotation in NGC 128 and that the gas distribution and kinematics in NGC 2768 is more nearly perpendicular to the major-axis (Fried & Illingworth 1994).

Kuijken et al. (1996) later studied a sample of 28 highly inclined S0s galaxies in a variety of environment, searching for counter-rotating stars. While no new system with counter-rotating stars was found, 4 of the objects displayed counter-rotating ionized-gas. This is $14 \pm 7\%$ of the entire sample or $24 \pm 10\%$ of the objects with detected emission.

Kannappan & Fabricant (2001) also searched for bulk counter-rotating ionized-gas in a sample of 67 galaxies from all morphological types, extracted from the Nearby Field Galaxy Survey (Jansen et al. 2000) to have both stellar and ionized-gas rotation curves available (Kannappan 2001). Those galaxies are generally fainter than in the above studies but better represent the local galaxy population. A total of 4 E/S0 gas counter-rotators were found, representing $7 \pm 3\%$ of the entire early-type sample or $24 \pm 10\%$ of those with both stellar and ionized-gas rotation curves. If only galaxies currently classified as S0s in NED are considered (including E/S0 and S0/a galaxies), the fractions become $6 \pm 4\%$ and $18 \pm 12\%$, respectively. Only one example of peculiar kinematics was found amongst 38 Sa-Sbc spirals, although in all cases the authors correctly argue that the number of counter-rotating objects identified represents a rather stringent lower limit.

Pizzella et al. (2004) searched for counter-rotation in a sample of 50 relatively bright and nearby S0/a–Scd galaxies for which major-axis stellar and ionized-gas kinematics are available from the literature (using similar observations and data analysis methods; see Bertola et al. 1996; Corsini et al. 1999; Vega Beltran et al. 2001; Corsini et al. 2003). They detect 2 gas counter-rotators only (they ignore the apparent counter-rotation in the outer disc of NGC 7213; see Corsini et al. 2003), all of which are S0s according to NED, for a fraction of $4 \pm 3\%$. If only galaxies currently classified as S0s are considered, the fraction becomes $20 \pm 13\%$. The low fraction of counter-rotators in intermediate and late-type spirals in this and the above study probably simply reflects again the fact that, in those systems, the counter-rotating gas is swept away by the dominant co-rotating one (independently of its origin).

In the current work, we detect 3 galaxies with counter-rotating ionized-gas in a sample of 30 objects. This represents $10 \pm 5\%$ of the entire sample, but the objects cover the morphological types S0–Sbc rather inhomogeneously, as they were primarily selected to cover a wide range of B/PS bulge morphologies. If we restrict ourselves to the objets classified as S0s in NED, the sample decreases to 14 but the 3 counter-rotating objects remain. They thus represent a fraction of $21 \pm 11\%$ of all the S0s, or $27 \pm 13\%$ of those where ionized-gas was detected. Those fractions are slightly higher than the aforementioned studies, presumably because of the better quality of the data, but they are consistent within the errors.

Merging the 5 samples discussed above, and keeping only galaxies currently classified as S0s in NED, we obtain a sample of 94 objects. Correcting obvious kinematic mistakes from the recent literature, but *not* carrying out a full literature search for each object, we find that 34 of those do not have detectable ionized-gas. Of the 60 objects that do, it is counter-rotating in 14. The fraction of objects with counter-rotating ionized-gas is thus $15 \pm 4\%$ for the entire S0 sample, or $23 \pm 5\%$ for the objects with detected ionized-gas only. Those fractions are again consistent with previous studies, but the errors have shrunk significantly.

4.2 Gas infall versus minor mergers

External gas acquired by a disc galaxy will generally settle in the equatorial plane, but it can also settle in the meridional one, forming a polar-ring or polar-disc structure (e.g. Tohline & Durisen 1982; Steiman-Cameron & Durisen 1982; Christodoulou et al. 1992). Once equilibrium has been reached, those configurations lead to co- or counter-rotating and perpendicular kinematics, respectively. Although the (normalised) cold and warm gas content of polar-rings is much higher than that of counter-rotators (the latter being similar to normal galaxies), this probably reflect different dynamical evolutions rather than different origins (i.e. massive self-gravitating polar-rings can be stable; Sparke 1986; Arnaboldi & Sparke 1994; Bettoni et al. 2001a).

Brocca, Bettoni & Galletta (1997) studied the environment of polar-ring galaxies and found it to be normal, in the sense of the closeness, size, and likelihood of interaction with nearby objects. Interestingly, there is at least one similarly-sized companion near almost all objects. An analogous study of galaxies with counter-rotating gas or stars by

Bettoni, Galletta & Prada (2001b) (who also considered the local density of galaxies on different spatial scales) finds similar results. While, superficially, this seems to indicate that counter-rotating material does not originate from recent interactions, it may also simply indicate that counter-rotation develops in rather standard conditions, and that the specific characteristics leading to counter-rotation (e.g. specific orbital configurations) are not captured by the coarse parameters considered.

From the ionized-gas statistics discussed above, external gas accretion is clearly a widespread phenomenom in S0 galaxies. A similar conclusion can be reached from an analysis of their neutral hydrogen (H I) and dust content (e.g. Wardle & Knapp 1986; Forbes 1991). The question remains, however, whether the external gas is accreted slowly and continuously (gas infall) or sporadically in lumps (minor interactions and mergers).

Using numerical simulations, Thakar & Ryden (1996) argue that gas infall is best suited for the creation of *massive* counter-rotating discs in spirals. Indeed, as long as it is not too clumpy and its infall rate is not too high, infalling gas will not unreasonably disturb and thicken the pre-existing galactic disc, while its angular momentum will determine the scalelength and formation time-scale of the counter-rotating disc. Furthermore, the clumpier the infalling gas, the smaller the counter-rotating disc (due to dynamical friction).

For a successful merging scenario, the satellite galaxy should be significantly less massive and dense than the host, otherwise a more spheroidal system will emerge and/or the disc will significantly thicken (e.g. Hernquist & Barnes 1991; Barnes 1992; Quinn, Hernquist, & Fullagar 1993; Bekki 1998; Balcells & Gonzalez 1998). While this is ill-suited for the formation of *massive* counter-rotating discs (as the merging time-scale is long and many such events are required to build up the mass; see, again, Thakar & Ryden 1996), it is probably befitting for the formation of the majority of counter-rotating discs which are spatially limited and thus (presumably) rather light, especially if the merging satellites are gas dominated.

We do not separate here between events where the satellite galaxies actually merge and events where simple tidally-induced transfers of material take place, since those are of a similar nature. It is nevertheless clear that tidally-induced gas accretion without merging is easier to reconcile with the requirement of keeping the host galaxy disc cold. Based on numerical simulations, Bournaud & Combes (2003) also argue in favor of accretion rather than merging in the case of polar-rings.

The presence of (likely) companions near all three galaxies discussed here, and the apparent disturbed structure of the counter-rotating gas in at least two of them, suggest that the counter-rotating gas was indeed accreted in one or perhaps at most a few discrete events. Other authors argue along similar lines for different objects (e.g. Haynes et al. 2000 for Sa galaxies). Based on the paucity of plausible nearby companions for their counter-rotators, Kannappan & Fabricant (2001) argue against tidally-induced mass transfer and favor (single) mergers, but they recognize that possible culprits may be hard to identify. In fact, the higher H_2/H I ratio observed in counter-rotating spirals (compared to polar-rings and normal galaxies) argues for the accretion of external material, as there should be increased atomic to molecular gas conversion near the co- to counter-rotating transition region (Bettoni et al. 2001a).

H I synthesis observations may actually represent the best hope of identifying "smoking gun" evidence for external gas accretion, since both faint galaxies and tidal features are most easily detected in H I. Data for a significant number of ionized-gas counter-rotators may thus go a long way toward identifying the origin of the counter-rotating material (or at least ruling out some possibilities). H I synthesis observations of the current sample of 3 counter-rotators have already been acquired and will be discussed in future publications (e.g. Chung et al. 2006 for NGC 1596).

4.3 Counter-rotating gas and bars

Given that the counter-rotating gas in NGC 128, NGC 1596 and NGC 3203 was discovered during a study of B/PS bulges, in which Chung & Bureau (2004) argued that the B/PS bulges of all three galaxies are in fact thick edge-on bars, it is worthwhile to ask if the counter-rotation itself might help us understand the structure, formation and evolution of those bulges.

As argued above, it is likely that the counter-rotating gas in all three galaxies was accreted from nearby objects during tidal interactions. It is thus entirely possible that the bars argued to be at the origin of the B/PS bulges were triggered by those same interactions. Indeed, it has been firmly established through numerical simulations that bar formation can be triggered or accelerated by gravitational interactions (e.g. Noguchi 1987; Gerin, Combes & Athanassoula 1990; Miwa & Noguchi 1998). Standard bar-driven evolution (e.g. gas inflows, buckling, redistribution of angular momentum) may then take over, most likely driving the galaxies toward earlier types and the bulges toward boxy and peanut shapes. Mihos et al. (1995) in fact present a simulation where a galaxy satellite is acccreted, triggering the formation of a bar which subsequently evolves into a B/PS bulge. Such a scenario is thus possibly at play in NGC 128, NGC 1596, and NGC 3203. The same interactions might also trigger bar formation in the satellite galaxies, if they are not accreted or destroyed in the process. This may in fact be the case in NGC 1596's companion NGC 1602, which is also barred. Independently of bar-driven evolution, it is of course also possible that minor mergers will lead to bulge growth and disc thickening, again driving the host towards earlier types.

The counter-rotating gas discs may also provide an independant test as to whether NGC 128, NGC 1596, and NGC 3203 are truly barred. Indeed, only rotating triaxial potentials possess stable counter-rotating periodic orbits which are inclined with respect to the equatorial plane (e.g., the so-called anomalous orbits; Magnenat 1982; Heisler, Merritt & Schwarzschild 1982; Mulder & Hooimeyer 1984). If the counter-rotating gas in the three galaxies is settled, as seems to be the case in NGC 128 and possibly in NGC 1596, then it must lie in such a configuration (see also Friedli & Udry 1993). Using integral-field spectroscopy, Emsellem & Arsenault (1997) clearly showed that this is the case in NGC 128, thus supporting the barred origin of its B/PS bulge, but NGC 1596 and NGC 3203 lack both integral-field spectroscopy and narrow-band imaging.

Although the above argument has not received much attention in the literature, integral-field and Fabry-Perot observations clearly show that the counter-rotating ionized-gas discs in the (nearly) edge-on S0 galaxies NGC 4546 (Plana et al. 1998; Sarzi et al. 2005) and NGC 7332 (Plana & Boulesteix 1996; Falcòn-Barroso et al. 2004) are also inclined, although they are also rather disturbed. Both are believed to be barred (e.g. Sandage & Bedke 1994; Falcòn-Barroso et al. 2004).

We also note that Friedli (1996) and Davies & Hunter (1997) discuss the development, evolution and kinematic signatures of counter-rotating bars in the presence of counter-rotating stars (see also Sellwood & Merritt 1994).

5 CONCLUSIONS

Using our previous studies of the ionized-gas and stellar kinematics of a relatively large sample of 30 edge-on disc galaxies with (mostly) boxy and peanut-shaped (B/PS) bulges, we have identified two new galaxies (NGC 1596 and NGC 3203) where the ionized gas is counter-rotating with respect to the bulk of the stars. We have also confirmed similar kinematics in one additional object (NGC 128). Counter-rotating gas is thus present in $10 \pm 5\%$ of our entire sample. However, if only lenticular (S0) galaxies are considered, the fraction climbs to $21 \pm 11\%$. This fraction further climbs to $27 \pm 13\%$ if only S0s with extended ionized-gas are considered. As discussed at length in the text, those fractions are consistent with but slightly higher than the few existing systematic studies available in the literature. Merging those studies, fractions of $15 \pm 4\%$ and $23 \pm 5\%$ are obtained for, respectively, all S0s and S0s with ionized-gas only.

Based on the presence of probable companions near the galaxies discussed here, we argued that minor mergers and tidally-induced transfer of material from nearby objects are primarily responsible for the counter-rotating gas. If accretion on to the objects is isotropic, similar processes must have been at work in roughly twice the fractions of objects discussed. This strongly argues for a non-negligible role of (minor) accretion in galaxy formation and evolution.

The presence of counter-rotating gas in barred galaxies offers a number of largely unexplored ways to probe the structure and dynamics of those objects. In edge-on galaxies in particular, where counter-rotation is easiest to detect, it offers an independent way of testing the barred nature of B/PS bulges.

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